# Fuzzy cognitive mapping for predicting hydromorphological responses to multiple pressures in rivers

**Stefan Lorenz[1], Vanesa Martinez-Fernández[2], Carlos Alonso[2], Erik Mosselman[3,4], Diego García de Jalón[2], Marta González del Tánago[2], Barbara Belletti[5], Dimmie Hendriks[3] and Christian Wolter[1]**

[1]*Leibniz Institute of Freshwater Ecology and Inland Fisheries, Müggelseedamm 301, 12587 Berlin, Germany;* [2]*Laboratorio de Hidrobiología, E.T.S.I. Montes, Universidad Politécnica de Madrid, Ciudad Universitaria s/n, 28040 Madrid, Spain;* [3]*Deltares, Rotterdamseweg 185, 2629 HD Delft, The Netherlands;* [4]*Faculty of Civil Engineering, Delft University of Technology, Stevinweg 1, 2628 CN Delft, The Netherlands; and* [5]*Department of Earth Sciences, University of Florence, Via Santa Marta 3, 50139 Florence, Italy*

## Summary

**1.** Different pressures often co-occur in rivers and act simultaneously on important processes and variables. This complicates the diagnosis of hydromorphological alterations and hampers the design of effective restoration measures.

**2.** Here, we present a conceptual meta-analysis that aims at identifying the most relevant hydromorphological processes and variables controlling ecological degradation and restoration. For that purpose, we used fuzzy cognitive mapping based on conceptual schemes that were created according to 675 scientific peer-reviewed river hydromorphology studies.

**3.** A model generated from this approach predicts responses that are consistent with common understanding of the direct interactions between hydromorphological pressures, processes and variables. However, it also leads to new knowledge beyond traditional hydromorphological models by dealing with the complex interactions of hydromorphology, vegetation, water chemistry and thermal regime.

**4.** Water flow dynamics appeared as the most important of all hydromorphological processes affected by simultaneously interacting pressures. Relevant processes such as vegetation encroachment and sediment entrainment are closely linked to water flow.

**5.** *Synthesis and applications*. Our results demonstrate the relevance of natural flow regime rehabilitation for river management. Hence, we suggest focusing primarily on rehabilitating the natural flow regime before carrying out extensive habitat restoration works. This challenging target in river rehabilitation could strongly increase the success of additional habitat restoration.

## Introduction

Water management shifted recently from quality-orientated targets to ecological integrity. This includes hydromorphology as a key component of river condition (e.g. Vaughan *et al.* 2009; Elosegi & Sabater 2013; Meitzen *et al.* 2013). Traditionally, the hydrological regime (i.e. quantity and dynamics of flow, connection to groundwater) was noted as the main driving force in rivers. Hydromorphological quality elements include this into a more holistic picture. They comprise river continuity (i.e. longitudinal and lateral connectivity of water and sediment transport and sorting) and river morphology (i.e. physical habitats, structural complexity and structure of bed, banks and the riparian zone).

Changes in hydromorphology are common in river systems (Fig. 1). In the USA, 44% of 0·9 million river and stream kilometres have been reported as impaired

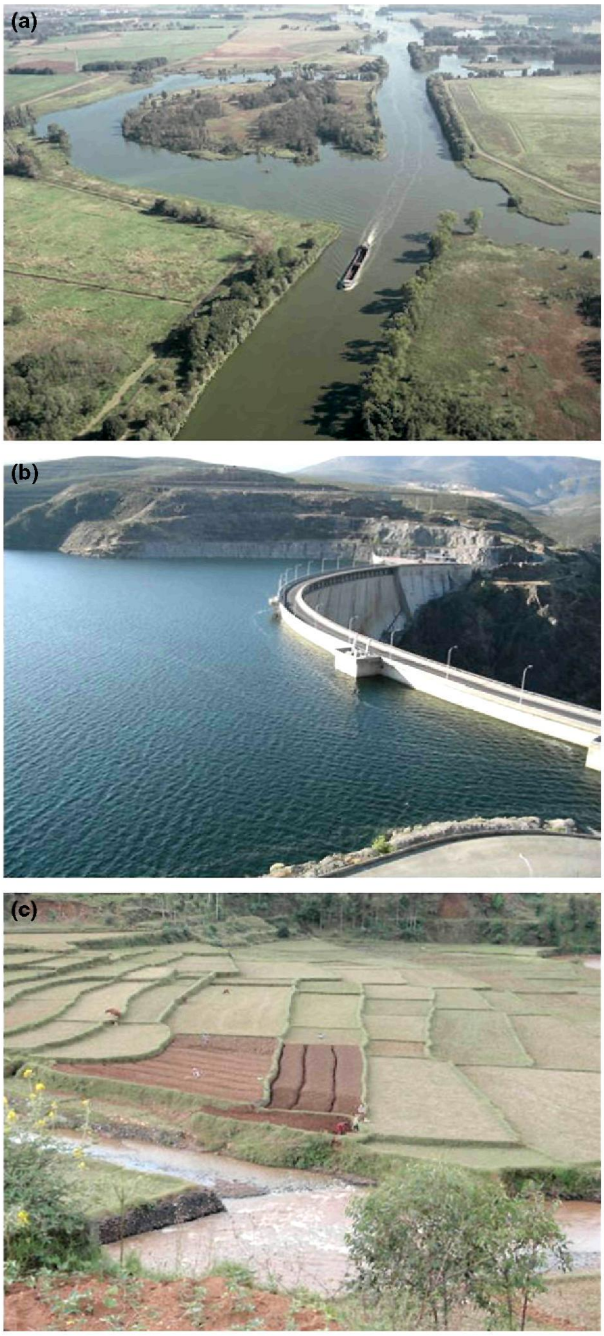


**Fig. 1.** Common hydromorphological modifications (HYMO pressures) of river systems found world-wide. (a) Cut meander in the Havel river (Germany) to support inland navigation. (b) Largest dam in the Lozoya river (Atazar dam, Spain) used for the water supply of Spain's capital city Madrid. (c) Water abstraction from an unknown tributary of River Mania (Madagascar) necessary to enable the production of rice.

(USEPA 2009). Hydrological modification by water diversions, channelization or dam construction is the second major source of impairment in these rivers behind agricultural use. Habitat alteration occurred in 23·2% of the impaired rivers, and flow alteration in 9·7%. In Europe, 64% of 1·17 million river kilometres have been reported not in good ecological status (EEA 2012). Hydromorphological or habitat alterations (hereafter referred to as *hydromorphology* in the context of this paper) are changes to the natural flow regime and river structure by modifications of bank structure, sediment and habitat composition, discharge regime, gradient and slope. Hydromorphological degradation of riparian zones and floodplains also reduce their natural retention of pollutants and can thereby increase the vulnerability of waters to other types of processes such as water chemistry (hereafter referred to as *other processes* in the context of this paper).

As already mentioned, hydrological and morphological pressures are important in rivers, but other pressures such as pollution often occur simultaneously, interlinked in a complex manner. Thus, each pressure cannot be seen as an individual driver of ecological change (Vaughan *et al.* 2009). The recent global trend in river water quality improvement lowers the effects of pollution on biota. However, a large number of typical riverine species still remain absent (EEA 2012). One potential limitation to recolonization of these species is continued impairment of hydromorphological conditions and, therefore, their fluvial habitats. Therefore, further investment on the recovery of fluvial habitats through the restoration of hydromorphological conditions might be necessary to restore the ecological integrity of rivers. Such detailed effects of changes in hydromorphology on ecosystem functioning have been recently reviewed (Elosegi & Sabater 2013). However, large uncertainties still exist (Elosegi & Sabater 2013; Meitzen *et al.* 2013; Pahl-Wostl *et al.* 2013). Such knowledge gaps call for more interdisciplinary approaches. But despite potentially shared knowledge bases of a variety of research areas (Meitzen *et al.* 2013), literature typically separates ecological and morphological studies.

To design ecologically effective restoration measures, the existing hydromorphological problems have to be clearly diagnosed. This, in turn, requires knowledge about the effects of hydromorphological processes, their intensity and their effects on the responding hydromorphological variables. This knowledge would ensure a physical habitat template, but in order to obtain successful restoration measures we also need knowledge about biological processes: initial colonization and ecological succession.

A large part of the reported uncertainties can be attributed to the complex interactions between hydrology, morphology, habitat (e.g. vegetation) development, chemistry and thermal regime. Furthermore, interactions and response might be site specific and, thus, difficult to generalize from one river to another. We present here a conceptual meta-analysis of a bibliographic review of peer-reviewed publications on field studies of river responses to degradation and restoration. Using fuzzy cognitive mapping (FCM), we aim at identifying the most relevant hydromorphological processes and variables that are involved in such complex interactions. We investigate the extent to which the FCM approach is able to explain the complex and synergistic relationships between hydromorphological processes and other processes such as water chemistry or pollution that control degradation–restoration processes. Our second objective is to improve current understanding of the complex mechanisms in multiple-stressor interactions that river management needs to address using simulations of common management scenarios.

## Materials and methods

### DEFINITION OF PRESSURES, PROCESSES AND VARIABLES

Hydromorphological (HYMO) pressures alter fluvial systems in their structure and composition through changes in the natural HYMO processes, which can be characterized by changes in particular HYMO variables and parameters. A HYMO process is a dynamic event that results in a transformation of a physical component of the fluvial system. For example, bed erosion is a HYMO process that transforms channel morphology and flow components. These transformations can be observed as changes in the morphology and structure of the river, but they also create a different environment that promotes changes in chemical components and in biological communities.

Every HYMO process is characterized by input and output values of the affected variables. We could evaluate the effects of these processes through selected state variables (e.g. substratum size, shear stress, flow magnitude) that can quantify the HYMO pressure. Usually, the modified variable triggers processes which in turn transform the values of that or other variables.

Therefore, process-based analysis of impacts relies on understanding systematic relationships between underlying physical components of hydrology and geomorphology, and subsequent biological responses. Table 1 summarizes the main HYMO pressures considered in this study and also other pressures triggered by the former. Three main blocks are considered: (i) pressures that affect the hydrological regime such as water abstraction or hydropeaking, (ii) pressures that modify the river connectivity and (iii) pressures that are related with morphological alterations such as impoundment and channelization. In the case of other pressures, thermal changes or eutrophication appears in specific cases.

### BIBLIOGRAPHIC REVIEW

The HYMO pressure typology developed in the iwrm.net project FORECASTER (see www.reformrivers.eu) was considered (Table 1). Based on 675 peer-reviewed publications (see Appendix S1 in Supporting Information for a detailed overview on references), we identified the processes and variables that are associated with the HYMO pressures considered. Particularly, a combination of HYMO features was used as key words for searching relevant literature published mainly in the last 20 years with Google Scholar (see Appendix S2 for a compilation of the key words used). We selected only studies that explicitly reported causal effects between HYMO pressures and biogeomorphic responses. The literature review includes a large range of European and North American river studies which concern a wide range of river types and pressures. However, the range of pressures and processes addressed by the paper mainly concerns temperate rivers.

Based on the reviewed documentation, we created 15 conceptual schemes showing qualitative interactions between HYMO pressures, processes and variables. The 15 conceptual schemes are reported in chapter 4 of the deliverable 1·2 of the REFORM project (Garcia de Jalón *et al.* 2013). As an

**Table 1.** Main pressures and hydromorphological (HYMO) (and other) processes considered in the conceptual schemes

Main pressures

| Hydrological regime | River fragmentation | Morphological alterations | Other pressures (not HYMO) |
|---|---|---|---|
| Surface & groundwater abstraction | Loss of longitudinal connectivity | Impoundment | Thermal changes |
| Increased flow | | Construction of large dam | Eutrophication |
| Regime modification | | Channelization | Organic discharge |
| Hydropeaking | | Meander rectification | |
| | | Alteration of riparian vegetation | |
| | | Alteration of in-stream habitat | |
| | | Embankment | |
| | | Sediment input | |
| | | Gravel extraction | |

Main HYMO processes

| Water flow dynamics | Sediment dynamics | Bank dynamics | Vegetation dynamics | Large wood dynamics | Aquifer dynamics | Other processes (not HYMO) |
|---|---|---|---|---|---|---|
| Water flow | Sediment entrainment | Bank erosion & failure | Vegetation encroachment | Large wood entrainment | Aquifer recharge | Primary production |
| | Sediment transport | Bank stabilization | Vegetation uprooting | Large wood transport | Aquifer discharge | Heat exchange |
| | Sedimentation | | Vegetation recruitment | Large wood deposition | | Redox |
| | Armouring | | | | | |

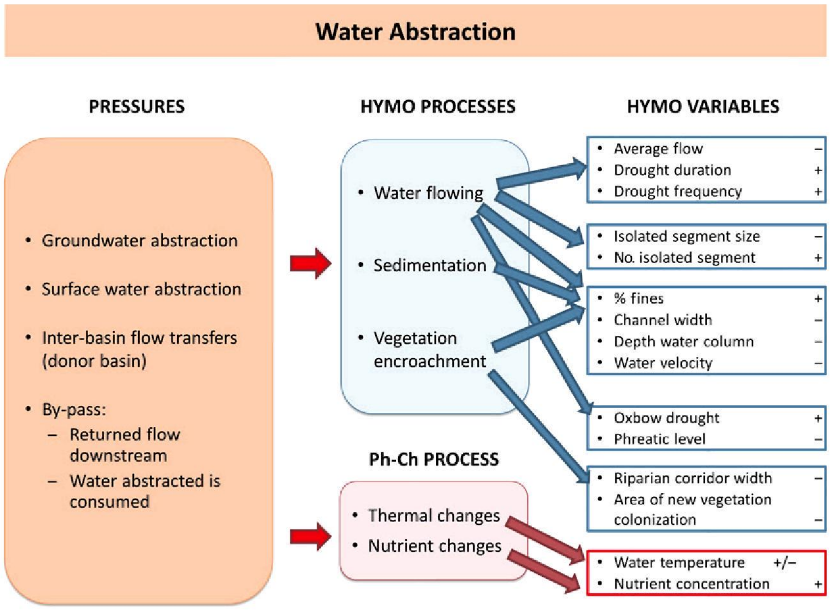


**Fig. 2.** Conceptual scheme referring to the pressure 'water abstraction'. The conceptual scheme comprises concepts (in this case pressures, processes and variables) connected by arrows that represent causal relationships between them, which could be positive or negative. Each connection is supported by at least one peer-reviewed publication, whenever no contradictions were found during the review process. The number of times that a specific relation was found was not considered, because a hydromorphological (HYMO) pressure more intensively studied through literature would have supposed a bias towards more studied topics.

example, Fig. 2 shows the conceptual scheme that refers to the pressure 'water abstraction'. Each conceptual scheme comprises concepts (in this case pressures, processes and variables) joined by directional edges (connections) that represent causal relationships between them, which could be positive or negative. Each connection is supported by at least one peer-reviewed publication, whenever no contradictions were found during the review process. We did not consider the number of times that a certain relation was found, because a HYMO pressure studied more intensively in the literature would have produced a bias. This review process resulted in one conceptual scheme for each pressure showing the induced process changes with respect to HYMO variables.

### IDENTIFICATION OF THE MOST RELEVANT HYDROMORPHOLOGICAL PROCESSES AND VARIABLES

We treated each developed conceptual scheme as an FCM obtained from scientific literature (according to Özesmi & Özesmi 2004) to identify the most relevant HYMO processes and variables. Appendix S3 explains the method and provides references for further reading. Hobbs *et al.* (2002), Özesmi & Özesmi (2004), and Tan & Özesmi (2006) also describe methodology, construction and ecological application of FCM in detail.

The conceptual schemes link pressures, processes and variables by causal relationships (Fig. 2). Responses are visualized by arrows. Arrows received values of −1 for negative relations and +1 for positive relations. The schemes were then transformed into mathematic adjacency matrices that represent which node of the scheme is adjacent to which other node. All separate matrices were then combined into one overall matrix representing a network of all analysed pressures. The values of arrows that occurred in multiple schemes were summed up, and then normalized by the total number of pressures. Thus, the causal links in the overall matrix are weighted in a continuous range between −1 and +1 according to their importance in the multiple-pressure network.

We calculated indegree (cumulative weight of connections entering a variable) and outdegree (cumulative weight of connections exiting a variable) of processes and variables. Centrality was calculated as a measure of process or variable influence in the network by summing up indegree and outdegree. A high centrality means that the variable or process is greatly affecting the system or that the variable or process is being affected by the system. In any case, a modification in the most central variables or processes (high centralities) would influence more greatly the total network with the specific consequences that it would suppose. We calculated complexity as a measure of possible system interference, density as a measure of network connectivity, and hierarchy as a measure representing the level of adaptation to change of the overall pressure network (Özesmi & Özesmi 2004). The matrix was used afterwards to calculate the FCM steady state and to ask 'what if' questions in various management scenarios (Özesmi & Özesmi 2004). First, we simulated the effects of single pressure removal on HYMO processes and variables. Secondly, we simulated the following scenarios that should represent hydromorphological impacts in a more precise manner because multiple HYMO pressures concur in river systems (Fig. 1).

*Scenario 1* simulates the main HYMO effects of meander cutting: meander rectification, channelization, alteration of riparian vegetation, alteration of in-stream habitat and embankment were given particular weighting. We expect channel gradient, flow velocity, sediment transport capacity and bed and bank erosion to increase (Erskine 1992).

*Scenario 2* simulates the main HYMO effects of the construction of a large dam: hydrological regime modification, river fragmentation, large dam & reservoir, alteration of riparian vegetation, alteration of in-stream habitat and loss of longitudinal connectivity were given particular weighting. This dam removal scenario concerns only 'large' dams (which act as reservoirs) and thus it concerns the effects of water abstraction and sedimentation within the reservoir. We expect changes in flow regime variables and the trapping of alluvial materials (Rood *et al.* 2005).

*Scenario 3* simulates the main HYMO effects of water abstraction from a river system: water abstraction and hydrological regime modifications were given particular weighting, hydropeaking received a low weight. We expect decreases in flow velocity and water depth, and increases in sedimentation (Dewson, James & Death 2007; James, Dewson & Death 2008).

## Results

The investigated overall HYMO pressure or impact system shows a high complexity value of 2·6. Complexity is the ratio of receiver to transmitter variables (Özesmi & Özesmi 2004). A high ratio (many receiver variables compared to transmitter variables ≙ high complexity) indicates that the system results in many outcomes and responses in relation to relatively few forcing pressures. Hierarchy was calculated as 0·0002, which corresponds to the relatively high complexity value and shows that the system is not hierarchically structured. Hierarchy indices equalling 1 would represent a fully hierarchical system, and systems showing hierarchy values close to 0 are 'more adaptable to local environmental changes because of their high level of integration and dependence' (Sandell 1996). The system had a density value of 0·036 indicating relatively complex causal relationships between pressures, variables and processes in the system compared to the total possible number.

The most central process in the network is the water flow dynamics, followed by vegetation encroachment, and sediment entrainment (Fig. 3). The higher centrality presented by the three processes is derived from the generation of outputs that affect other processes and variables (high outdegree scores, Fig. 3); hence, they present relevance in influencing other HYMO processes and variables. Analyses of HYMO processes' indegree (Fig. 3) showed that bank stabilization and water flow dynamics are affected most by the pressures. The most central variables in the network are thalweg elevation and channel width, followed by riparian cover area, large woody debris, and phreatic level (Fig. 3).

A comparative overview of the percentages of variables changed by single pressure removals shows that increased flow and meander rectification affect most of the HYMO processes and variables (see Figure S1, Tables S1 & S2). Removing for example increased flow resulted in strong decreases of the processes water flow dynamics, aquifer recharge, sediment transport, and bank erosion and failure, and of the variable of phreatic level. According to the simulation, the main effect of removing the single pressure meander rectification was a strong increase in aquifer recharge. Further, removing meander rectification would mainly lead to a decrease of water flow dynamics, sediment transport and entrainment, large wood entrainment, armouring, vegetation uprooting, bank erosion & failure and also to a decrease in water column depth.

The changes in HYMO processes and variables from our management option simulations of Scenarios 1–3 are presented in Fig. 4. In Scenario 1, 78% of all processes and

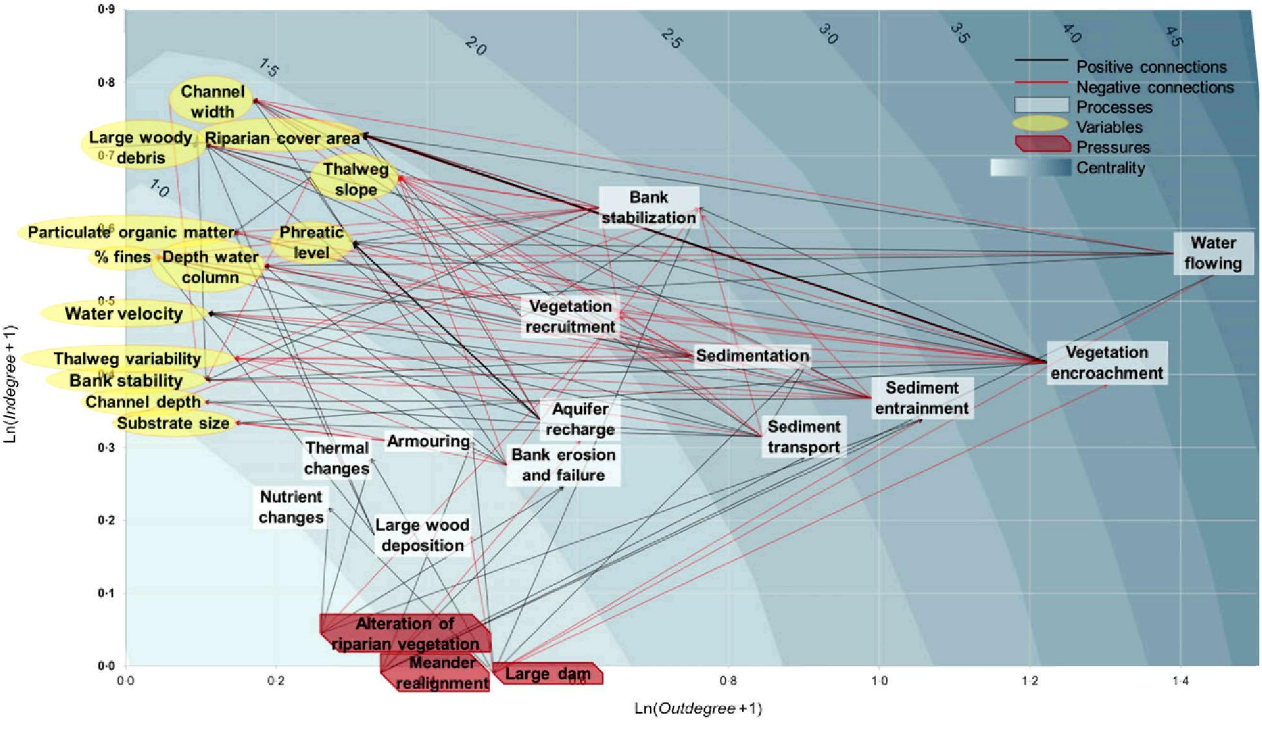


**Fig. 3.** Cognitive interpretation diagram of the interactions between pressures, processes and variables. Only pressures/processes/variables with centralities ≥0·5 are drawn. Thresholds of centrality are plotted as coloured backgrounds, the darker the greater centrality, that is greater influence by affecting or being affected within the system. The thickness of the lines indicates strength of the connections. Black and red lines represent positive and negative connections, respectively. A positive connection indicates an excitatory relationship, that is as 'A' increases 'B' increases, while a negative connection indicates an inhibitory relationship, that is as 'A' increases 'B' decreases.

variables are affected. Sediment entrainment (process) and water column depth (variable) received the strongest changes. In Scenarios 2 and 3, 70% and 65% of all processes and variables are affected, respectively. Scenario 2 caused profound changes in the processes water flow dynamics, armouring and thermal changes, and in the variables drought duration, water temperature and nutrient concentration. Scenario 3 changed water flow dynamics too, but also caused strong increases in vegetation encroachment. Scenario 3 profoundly changed the variables drought duration, % fines, riparian cover area, large woody debris and particulate organic matter. Figure S2 gives details of the steady-state conditions of the system.

## Discussion

Human pressures affecting rivers do not come alone, as many elements of the riverine environment covary (Vaughan *et al.* 2009). The resulting ecological changes in such situations could be a response to any or all of the changes associated. Their effects could be additive, subtractive or multiplicative. Our multi-step FCM approach enables us to explain such complex systems as it incorporates a large number of variables that might interact.

In its steady state, the model describes the situation of the HYMO processes and variables according to the conditions commonly found in hydromorphologically altered large river systems (Figure S2). Erskine (1992), Batalla, Gomez & Kondolf (2004), and Magilligan & Nislow (2005) showed that drought duration, drought frequency, and thalweg elevation are relatively low in such rivers due to channelization and water regulation. Dewson, James & Death (2007) and James, Dewson & Death (2008) demonstrated enhanced nutrient concentrations, water temperature, % fines, and phreatic level. The reliable output for the steady state suggests that our management option simulations should yield reliable output as well. However, the demonstrated effect sizes of processes and variables reflect only increases or decreases relative to steady state, or to other processes and variables affected at the same time. Thus, results should be interpreted in a qualitative rather than quantitative manner (Tan & Özesmi 2006).

The results of our scenario simulations (Fig. 4) reflect responses to common management practices. Meander cutting (Scenario 1) is a typical component of channelization, increasing channel gradient, flow velocities, sediment transport capacity and bed and bank erosion (Erskine 1992). The model correctly predicted increases in channel slope, channel incision and bed armouring following channel straightening (Erskine 1992). Downstream impacts of large dams (Scenario 2) often follow from three types of environmental alterations: (i) changes in flow regime (quantity and timing); (ii) trapping of alluvial materials, and (iii) fragmentation of the river corridor (Rood *et al.* 2005). We also noticed previously reported changes in minimum and maximum flow duration, and a decreasing variability of mean daily flows and flood magnitude (Batalla, Gomez & Kondolf 2004; Magilligan & Nislow 2005). Water abstraction (Scenario 3) is known to decrease flow velocity, water depth, and channel width, to increase sedimentation and particulate organic matter retention, and to change thermal regime and water chemistry (Dewson, James & Death 2007; James, Dewson & Death 2008).

The findings of Scenarios 1 and 2 are confirmed by existing physics-based hydromorphological models (e.g. Jansen *et al.* 1979; Kerssens & Van der Zwaard 1980). However, so far hydromorphological models are not able to deal with system behaviour resulting from interactions with chemistry and vegetation dynamics as predicted by Scenario 3. Our model includes such interactions owing to its conceptual basis. Our approach could therefore provide reliable output based on cumulative knowledge from various sources, including the possibility of adaptation to improved knowledge at any stage of modelling. Contrary findings in literature, however, may question model output for specific cases (Erskine 1992; Dewson, James & Death 2007; James, Dewson & Death 2008). The state of the relevant variables identified by our model is likely to vary considerably between river types, for example between mid-sized and large rivers, lowland and highland rivers, or gravel-bed and sand-bed rivers. Further, effects on variables such as temperature and nutrients can differ widely depending on e.g. dam characteristics in our Scenario 2 (such as size and operation of the dam or the amount of abstracted water). Depending on specific hydromorphological impacts or the river region in focus, the model variables might be adjusted according to their relative importance and weight. We expect that the model will yield discriminative pressure effects that explain the aforementioned contrary findings (Erskine 1992; Dewson, James & Death 2007; James, Dewson & Death 2008).

We identified water flow dynamics as the most relevant HYMO process affecting HYMO variables (Fig. 3). This may seem trivial as water flowing through channels, floodplains, and riparian areas is the fundamental process that drives fluvial dynamics. However, it is not trivial that water flow dynamics emerged as much more important than other simultaneously interacting pressures. In other words, improving the flow regime could probably improve riverine ecology before any other rehabilitation measure. This might also explain the reported failure of rehabilitation by providing habitat structures without improving the flow regime (e.g. Jähnig *et al.* 2010; Palmer, Menninger & Bernhardt 2010). This result further underlines the importance of environmental flow approaches, and suggests a certain priority of the natural flow regime before extensive habitat restoration works.

### CONCLUSIONS

This paper presents an approach consisting of a novel application of Fuzzy Cognitive Mapping to identify the complex causal relationships among hydromorphological pressures, processes and variables that are likely to have

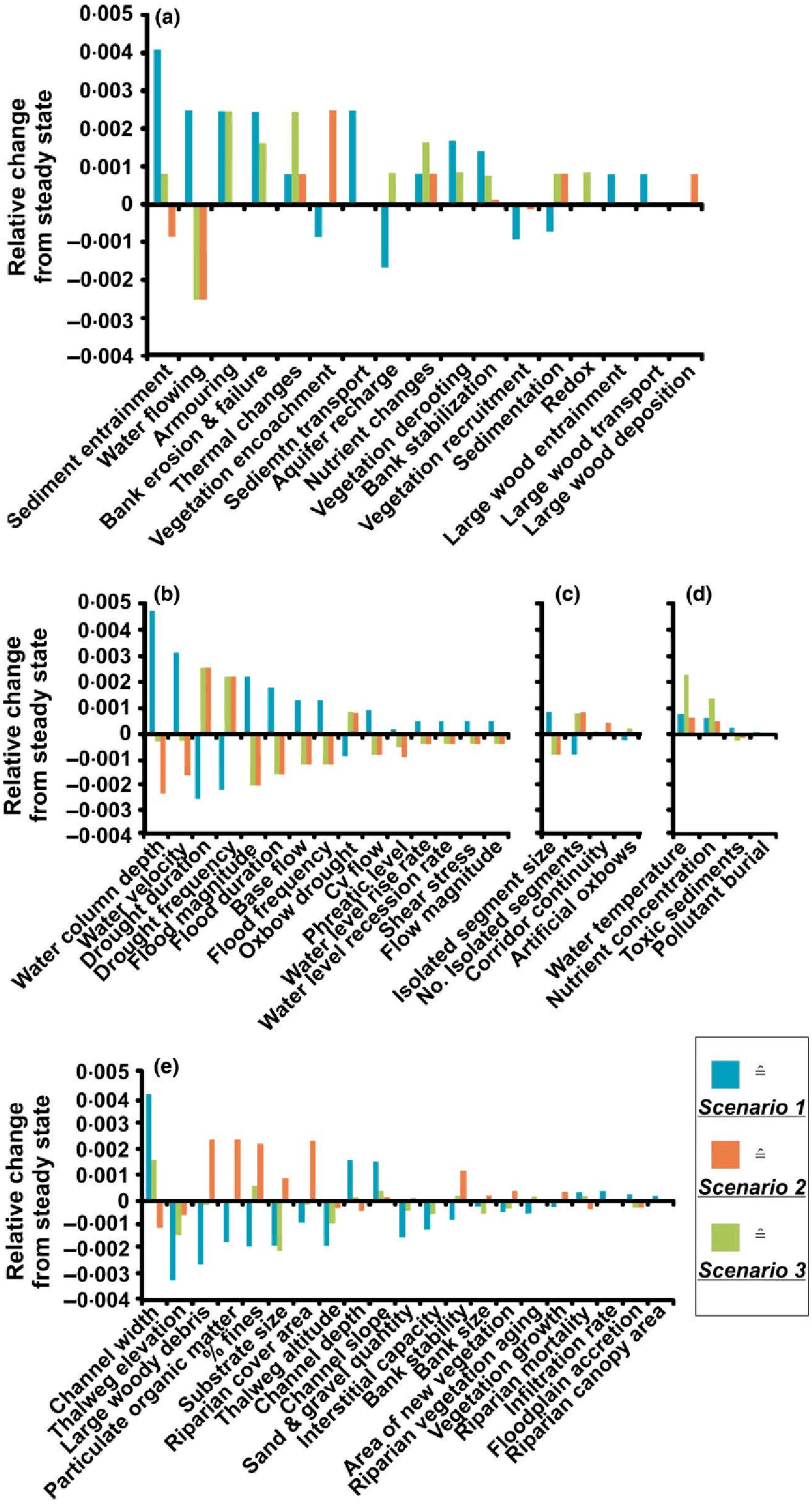


**Fig. 4.** Management option effects (= relative changes from steady state) on (a) hydromorphological processes, (b) hydrological regime variables, (c) river continuity variables, (d) other variables and (e) variables representing morphological conditions. Scenario 1 = meander cutting; Scenario 2 = construction of large dams; Scenario 3 = water abstraction. Processes and variables are ordered by decreasing magnitude of change.

key effects on river degradation and restoration. Our FCM meta-analysis has enabled us to summarize a large body literature on river HYMO in terms of a graphical and semi-quantitative model.

Uncertainties in multiple-pressure interactions hamper the selection of relevant processes and variables for river management. As expected, the FCM meta-analysis showed that water flow dynamics is the primary driver of change in altered systems. Hence, our results point on the relevance of natural flow regime rehabilitation for river management. Our results suggest that in rivers with natural flow dynamics, the success of habitat restoration works could strongly increase. Otherwise, habitat restoration might be even unsuccessful to a certain point. However, the rehabilitation of natural flow dynamics appears as the most challenging target in river restoration.

## Acknowledgements

This research was supported by the European Union 7th Framework Project REFORM under contract no. 282656. We are grateful to three anonymous reviewers for their helpful comments on an earlier version of this manuscript.

## Data accessibility

Bibliographic review: uploaded as online supporting information. Conceptual schemes: available at www.reformrivers.eu in FP7 REFORM deliverable 2.1 'Review on pressure effects on hydromorphological variables and ecologically relevant processes.'

## References

Batalla, R.J., Gomez, C.M. & Kondolf, G.M. (2004) Reservoir-induced hydrological changes in the Ebro River basin (NE Spain). *Journal of Hydrology*, **290**, 117–136.

Dewson, Z.S., James, A.B.W. & Death, R.G. (2007) Stream ecosystem functioning under reduced flow conditions. *Ecological Applications*, **17**, 1797–1808.

EEA (European Environmental Agency) (2012) European waters - assessment of status and pressures. European Environmental Agency Report No 8/2012.

Elosegi, A. & Sabater, S. (2013) Effects of hydromorphological impacts on river ecosystem functioning: a review and suggestions for assessing ecological impacts. *Hydrobiologia*, **712**, 129–143.

Erskine, W.D. (1992) Channel response to large scale river training works: Hunter River, Australia. *Regulated Rivers: Research & Management*, **7**, 261–278.

Garcia de Jalón, D., Alonso, C., González del Tanago, M., Martinez, V., Gurnell, A., Lorenz, S. *et al.* (2013) Deliverable D1.2: Review on pressure effects on hydromorphological variables and ecologically relevant processes. REFORM Deliverable Report to the European Union.

Hobbs, B.F., Ludsin, S.A., Knight, R.L., Ryan, P.A., Biberhofer, J. & Ciborowski, J.J.H. (2002) Fuzzy cognitive mapping as a tool to define management objectives for complex ecosystems. *Ecological Applications*, **12**, 1548–1565.

Jähnig, S.C., Brabec, K., Buffagni, A., Erba, S., Lorenz, A.W., Ofenböck, T., Verdonschot, P.F.M. & Hering, D. (2010) A comparative analysis of restoration measures and their effects on hydromorphology and benthic invertebrates in 26 central and southern European rivers. *Journal of Applied Ecology*, **47**, 671–680.

James, A.B.W., Dewson, Z.S. & Death, R.G. (2008) Do stream macroinvertebrates use instream refugia in response to severe short-term flow reduction in New Zealand streams? *Freshwater Biology*, **53**, 1316–1334.

Jansen, P.Ph., Van Bendegom, L., Van den Berg, J., De Vries, M. & Zanen, A. (1979) *Principles of River Engineering; The non-Tidal Alluvial River*, 1st edn. Pitman, London, UK.

Kerssens, P.J.M. & Van der Zwaard, J.J. (1980) *Hydraulic and Morphological Impacts of Dam Construction*. Delft Hydraulics Publication No.238, Delft, the Netherlands.

Magilligan, F.J. & Nislow, K.H. (2005) Changes in hydrologic regime by dams. *Geomorphology*, **71**, 61–78.

Meitzen, K.M., Doyle, M.W., Thoms, M.C. & Burns, C.E. (2013) Geomorphology within the interdisciplinary science of environmental flows. *Geomorphology*, **200**, 143–154.

Özesmi, U. & Özesmi, S.L. (2004) Ecological models based on people's knowledge: a multi-step fuzzy cognitive mapping approach. *Ecological Modelling*, **176**, 43–64.

Pahl-Wostl, C., Arthington, A., Bogardi, J., Bunn, S.E., Hoff, H., Lebel, L. *et al.* (2013) Environmental flows and water governance: managing sustainable water uses. *Current Opinion in Environmental Sustainability*, **5**, 341–351.

Palmer, M.A., Menninger, H. & Bernhardt, E.S. (2010) River restoration, habitat heterogeneity and biodiversity: a failure of theory or practice? *Freshwater Biology*, **55**, 205–222.

Rood, S.B., Samuelson, G.M., Braatne, J.H., Gourley, C.R., Hughes, F.M.R. & Mahoney, J.M. (2005) Managing river flows to restore floodplain forests. *Frontiers in Ecology and the Environment*, **3**, 193–201.

Sandell, K. (1996) Sustainability in theory and practice: a conceptual framework of eco-strategies and a case study of low-resource agriculture in the dry zone of Sri Lanka. *Approaching Nature from Local Communities: Security Perceived and Achieved* (ed. A. Hjort-af-Ornäs), pp. 163–197. Linköping University, Linköping, Sweden.

Tan, C.O. & Özesmi, U. (2006) A generic shallow lake ecosystem model based on collective expert knowledge. *Hydrobiologia*, **563**, 125–142.

USEPA (United States Environment Protection Agency) (2009) *National Water Quality Inventory: Report to Congress. 2004 Reporting Cycle*. United States Environmental Protection Agency, Office of Water, Washington, DC.

Vaughan, I., Diamond, M., Gurnell, A., Hall, K.A., Jenkins, A., Milner, N.J. *et al.* (2009) Integrating ecology with hydromorphology: a priority for river science and management. *Aquatic conservation: Marine and Freshwater Ecosystems*, **19**, 113–125.

*Received 23 June 2015; accepted 3 November 2015*
*Handling Editor: Shelley Arnott*

## Supporting Information

Additional Supporting Information may be found in the online version of this article.

**Figure S1.** Percentages of variables changed by single pressure removals.

**Figure S2.** Steady-state conditions of the hydromorphological pressures, processes and variables in the hydromorphological pressure/impact system.

**Table S1.** Effects of hydromorphological pressure removal on hydromorphological processes identified in the conceptual schemes. Effect sizes range from strongly negative (—) to strongly positive (+++), 0 = no effect.

**Table S2.** Effects of hydromorphological pressure removal on hydromorphological variables identified in the conceptual schemes. Effect sizes range from strongly negative (—) to strongly positive (+++), 0 = no effect.

**Appendix S1.** References used for the bibliographic review.

**Appendix S2.** Key-words used for the Google Scholar literature search.

**Appendix S3.** Methodology on the identification of the most relevant hydromorphological processes and variables using fuzzy logic cognitive maps.